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Carbon sequestration in a tropical landscape: an economic model to measure its incremental cost*

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Abstract

Farm level rates of carbon sequestration are derived for timber and agroforestry systems based on *Paraserianthes falcataria*. An economic model is used to measure the incremental cost of carbon storage, based on the opportunity cost of land diverted from annual crop production. The method is applied to the Manupali watershed, in the Philippine province of Bukidnon, to estimate carbon storage potential and carbon storage costs at a landscape scale. Carbon storage via land use modification is calculated to cost between \$3.30 per ton on fallowed lands and \$62.50 per ton on land that otherwise supports high value cropping. Carbon storage through agroforestry is less costly than via a pure tree-based system; a strong argument for the role of agroforestry rather than forestry per se, in re-forestation projects.

Introduction

The accumulation of greenhouse gases in the upper atmosphere is a global concern, and finding low-cost methods to sequester carbon is emerging as a major international policy goal. At current greenhouse gas emission rates average global surface temperature is expected to rise by approximately 0.3-2.5 °C in the next fifty years and 1.4-5.8 °C in the next century (Houghton 1996; Houghton et al. 1992; Watson et al. 1998). Although the economic and ecological consequences of global warming continue to be debated (Reddy and Price 1999), many scientists believe that costs will likely outweigh benefits (Bruce et al. 1996). To date, most interest has focused on carbon dioxide, which is the most important greenhouse gas (Heath et al. 1996; Manne and Richels 1991). The United Nations Framework Convention on Climate Change (the Kyoto Protocol) provides a mechanism by which a country that emits carbon in excess of agreed-upon limits can purchase carbon offsets from a country or region that manages carbon sinks. Some observers suggest that through this Clean Development Mechanism (CDM), a ratified Kyoto Protocol could reduce rural poverty by extending payments to low-income farmers who provide carbon storage (Smith and Scherr 2002). However, the Protocol leaves many details regarding carbon trading undetermined. Furthermore, questions remain as to the cost-effectiveness of carbon sequestration on low-income farms, and how payments for carbon storage might be implemented in practice (Frumhoff et al. 1998).[1]

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[1]Space limitations preclude an in-depth discussion of many important details of climate change, the Kyoto Protocol, and research on carbon sequestration in the low-income tropics. Interested readers should consult the Intergovernmental Panel on Climate Change

This paper focuses on measuring the costs of carbon storage on low-income farms in the Philippines, which ranks seventh among the top twenty tropical countries in ability to sequester carbon (Trexler and Haugen 1995). An "opportunity cost" method for valuing the carbon storage potential of an agricultural area is presented. This opportunity cost is based on the value of agricultural land and the opportunity cost of converting fallow and agricultural land to forest and agroforest. A payment stream that would be necessary to compensate farmers for engaging in forestry and agroforestry for the purpose of carbon sequestration is computed. Based on this payment stream, a schedule of per-ton carbon prices are derived for a range of existing land uses and types. Data are then weighted and aggregated to a watershed scale.

Data and study site

Site description

Data come from the Manupali watershed, in the Philippine province of Bukidnon. The watershed is located on the southern island of Mindanao and drains into the Pulangi River, covering an area of approximately 60,000 hectares. More than 40 percent of the watershed is hilly, average annual temperature is 18.5 degrees Celsius, and average precipitation is 2400 mm. The watershed can be classified into four geomorphic units: mountains (1400-1900 meters above sea level (masl)), upper footslopes (700-1400 masl), lower footslopes (370-700 masl), and alluvial terraces (320-370 masl) (West et al. 1997). Farm size in the upper foothills is on average 3.5 ha (Poudel et al. 1998). Major crops grown in the watershed are maize (*Zea mays*), sugarcane (*Saccharum officinarum*) and rice (*Oryza sativa*) in the lower elevations, and maize, various vegetables, and coffee (*Coffea spp.*) in the upper elevations. Agriculture occupied approximately 50 percent of watershed area in 1994, and 7 percent of land at slopes of 40-90 percent was devoted to agriculture. On marginal hillside farms productivity tends to be very low: average maize yields during 1994-96 were less than 500 kg ha^{-1} and average vegetable yields were approximately 2700 kg ha^{-1} (Coxhead et al. 2002).

Experiment and farm survey data

Agricultural opportunity costs are based on data from household surveys conducted in the watershed and farm-level programming and simulation models (Shively and Zelek 2002). The main parameters used in the farm models are listed in Table 1. Opportunity costs are computed for 10-year planning periods based on two classes of farms: high-input, crop-intensive vegetable farms and low-input maize farms. The choice of a 10-year planning horizon is based upon the anticipated choices of farmers to leave the tree studied here, *Paraserianthes falcataria*, in place for this length of time, given that this will be close to optimal in terms of annualized returns.[2] Table 1 contains input and output prices and lists input levels and crop shares for each representative class of farm. The latter were derived as choice variables in a farm optimization model. Outputs listed in Table 1 include income levels, both from agricultural and non-agricultural endeavors, and crop output. Expected farm incomes differ substantially according to input levels and crop choice. For example, year one income for the low-input farm is 26,257 pesos and income for a high input farm is 113,477 pesos (in 2001, \$1US= 51 pesos). These Figures reflect the types of crops grown and the influence of underlying land quality on levels of productivity. Consistent with patterns in the data, we assume that low-input farms have surplus labor that is sold on the local labor market to derive non-agricultural income. High-input farms derive all income from agricultural sources and hire workers to supplement family labor.

Calculating rates and levels of carbon storage

Carbon is stored in vegetation when plants convert gaseous carbon dioxide into structural carbon via photosynthesis. For trees, the amount of carbon stored increases in parallel with tree biomass until they reach maturity, at which point carbon storage reaches a steady state. Forest carbon is stored not only in tree biomass, but also in under-storey vegetation, soils, and floor litter. Some carbon is released when trees

(www.ipcc.ch), the UN Framework Convention on Climate Change (http://unfccc.int/), and the climate change working group of the Alternatives to Slash and Burn (ASB) Program (www.asb.cgiar-.org/climate_change.shtm).

[2]In practice, the exact timing of tree harvest will depend upon personal characteristics of growers, such as cash needs, and market conditions, such as prices for or logs of varying diameters.

Table 1. Data used in the household model to derive incremental cost of carbon sequestration in Manupali watershed in the Philippines

	Low-Input Farms	High-Input Farms
Parameters		
Vegetable price (pesos/kg)	6.50	6.50
Maize price (pesos/kg)	5.66	5.66
Fertilizer price (pesos/kg)	7.00	7.00
Pesticide price (pesos/liter)	421.50	421.50
Variables		
Fertilizer input (kg)	136	211
Labor input (man days)	100	150
Pesticide input (liters)	0.00	3.0
Vegetable share	0.00	1.00
Maize share	1.00	0.00
Hired labor (man days)	0	50
Labor sold (man days)	200	0
Outputs		
Total income (pesos)	26,257	113,477
Non ag income (pesos)	13,000	0
Agricultural income (pesos)	13,257	113,477
Vegetable yield (3x/yr) (kg/ha)	0.00	5,217
Maize yield (2x/yr) (kg/ha)	2,039	0

Note: Results are for year one of a 10-year simulation. Values are reported in Philippine pesos (in 2001, $1US= 51 pesos).

are harvested. Carbon in non-merchantable portions of trees such as branches and leaves, and most of the carbon stored in litter and under-story vegetation is released back into the atmosphere within a decade (Heath et al. 1996). Further carbon is released in merchantable timber through processing and use as fuel. However, some carbon remains in storage in end-use products such as lumber used in furniture and house construction. Although annual crops are capable of providing some degree of long-term carbon storage in the root zone, for current purposes it is assumed that no carbon is stored by annual crops.

Carbon (C) stored in the tree-based system at time t is an increasing function of above and below ground biomass (B) at time t, that is, $C_t = f(B_t)$. Levels of carbon sequestration in two tree-based systems are based on a representative one-hectare plot of *Paraserianthes falcataria,* a fast growing tropical tree species (Uriarte and Pinol 1996). *P. falcataria* has been grown successfully in tree plantations in the Philippines and the tree can be readily incorporated into agroforestry systems. The above ground biomass density of the tree stand and the total merchantable timber volume associated with a plot are computed following the procedure outlined by Uriarte and Pinol (1996) and the biophysical relationships described by Brown (1997). Uriarte and Pinol's equations are specific to sites in Mindanao. Below ground biomass is estimated using relationships reported by Enquist and Niklas (2002) for a closely related species. Estimates of above ground and below ground biomass are combined to render the total biomass of the stand, employing the conservative estimate that 70 per cent of stored carbon is released through the harvest process and end uses, and the remaining 30 per cent is captured in end uses and below ground biomass (Brown 1997; Enquist and Niklas 2002). Using the computed measure of total permanently stored biomass, the amount of carbon sequestered in the stand is derived using a carbon conversion factor. This provides the total amount of carbon stored in tons per hectare.[3] The computation of carbon is formalized by defining four parameters:

D=wood density (specific gravity) of species (= 0.25 for *P. falcataria*)

Q=soil (site) quality index (ranges from 14 − 46 for this study)

[3]Given that this estimate of carbon storage is constructed from data collected in the Manupali watershed and relationships derived mainly from similar sites, a high degree of accuracy in the estimate is expected. It must be recognized, however, that differences in growing conditions across sites and agroecological zones could reduce the accuracy of estimated carbon Figures and limit one's ability to generalize findings to other sites.

F=proportion biomass composed of carbon (= 0.45 for *P. falcataria*)
S=spacing (product of within and between row spacing, in meters),
And eight variables:
A_t=age of stand at time t (years)
B_t=merchantable tree stand biomass at time t (metric tons)
C_t=carbon stored at time t (metric tons)
E_t=biomass expansion factor at time t (to convert merchantable biomass into total above ground biomass accounting for limbs and leaves at time t)
M_{at}=total above ground biomass of stand at time t (metric tons)
M_{rt}=Root biomass (metric tons)
T_t=Total biomass at time t (in tons)
V_t= volume of stand at time t (board volume in cubic meters).

Using these definitions, carbon storage for *P. falcataria* can be modeled as evolving over time according to a set of seven equations, as described below.

To measure volume, a formula derived in Mindanao, Philippines for stands of a closely related species, *Albizia falcataria*, is used (Uriarte and Pinol 1996). Volume accumulates according to age, spacing and site quality, which for this study is based on site index estimates for the Manupali watershed reported by Bin (1994):

$$V_t = 10^{2.94469-(1.4139/A_t)-.210044*\ln(S)-7.84248/Q}. \tag{1}$$

Biomass at a specific age is assumed to be a product of volume and a constant tree density:

$$B_t = V_t * D. \tag{2}$$

Merchantable biomass depends on the expansion factor for biomass, which differs across species. For *Paraserianthes falcataria* the factor is taken from Brown (1997), who posits the following relationship:

$$E_t = e^{3.213-0.506\ln(B_t)} \text{ for } B_t < 190, \text{otherwise } 1.74. \tag{3}$$

Total above ground biomass is a simple product of the expansion factor and biomass:

$$M_{a\,t} = E_t * B_t. \tag{4}$$

Enquist and Niklas (2002) provide a relationship between above and below ground biomass. The latter is computed as a function of the former according to:

$$M_{rt} = \left(\frac{M_{at}}{3.88}\right)^{\frac{1}{1.02}}. \tag{5}$$

Total biomass is the arithmetic sum of above and below ground biomass:

$$T_t = M_{at} + M_{rt}. \tag{6}$$

Carbon storage depends on total biomass and a carbon storage factor. The carbon storage factor used here is that reported by Trexler and Haugen (1995):

$$C_t = M_{at} + M_{rt}. \tag{7}$$

Equation (1)-(7) are based on specific tree spacing and a site quality index that ranges from 14-46. Equation (7) gives the amount of carbon stored in trees in tons ha^{-1}. The final accumulation of carbon (C) stored in a system from time $t = 0$ to T is:

$$C = \sum_{t=0}^{T} \left(C_t - C_{t-1}\right). \tag{8}$$

Detailed data on harvest values, establishment costs, and maintenance costs for *P. falcataria* are reported by Zelek and Shively (2003), where data on differential costs for agroforestry vs. forestry are based on the results of Nissen, Midmore and Keeler (2001). In general, higher quality land produces more valuable harvests. For example, the value of a tree harvest on land of the lowest quality is 138,000 pesos while the value on land of the highest quality is 338,000 pesos. These differences reflect differences in tree biomass. Larger trees grow on lower elevations and better soils, which in turn yield merchantable timber at a faster rate than trees at higher elevations or on poor soils. Table 2 presents carbon sequestration rates for each site quality index. The indices range from land of lowest quality to highest quality. As land quality increases, the potential amount of carbon sequestered on that land increases due to enhanced growing capacity. The total amount of carbon stored in year 10 on the lowest quality land is 72 tons per ha. The amount stored on the highest quality land is 112 tons per ha.

Table 2. Estimated cumulative carbon storage by year and site index in Manupali watershed in the Philippines

	Site Index								
Year	14	18	22	26	30	34	38	42	46
1	37	43	47	50	52	54	56	57	58
2	49	56	61	65	68	71	73	74	76
3	56	64	70	75	78	81	83	85	87
4	60	70	76	81	85	88	90	92	94
5	64	73	80	85	89	93	95	97	99
6	66	76	83	89	93	96	99	101	103
7	68	78	86	91	96	99	102	104	106
8	70	80	88	93	98	101	104	106	108
9	71	82	89	95	99	103	106	108	110
10	72	83	91	96	101	104	107	110	112

Note:Values illustrate the total carbon sequestered (in metric tons) on a 1 ha plot of P. falcataria with 5 m×2 m spacing.Source: computed by the authors using equations reported in the text and site indexes reported by Bin (1994).

Economic model

Carbon prices are estimated by minimizing a stream of annual payments subject to the condition that farmers remain "just as well off" maintaining a tree plantation (or agroforest) as harvesting trees and switching to agriculture for the remainder of the planning horizon. This payment stream can be derived as the solution to an intertemporal optimization problem for each type of farm type and index of site quality. The problem in a pure tree-based system is to choose a stream of annual payments $\{P_t\}$, to minimize:

$$\sum_{t=0}^{T} \beta^{t-1} P_t, \tag{9}$$

subject to the indifference constraint:

$$P_t\delta_t - E_t - M_t \geq A_t + H_t - P_tC_tX, \tag{10a}$$

where $0 \leq \beta \leq 1$ is the annual payment at time *t*, δ_t is the addition to the carbon stock at time *t*, E_t is the establishment cost of the tree stand at time *t* (positive in year one and otherwise zero), M_t is the tree maintenance cost at time *t*, A_t is the agricultural opportunity cost at time *t*, H_t is the harvest value (if any) of the tree stand at time *t*, C_t is the total amount of carbon stored in the tree stand at time *t*, and X is the carbon release rate if the trees are harvested (the 70 percent Figure cited above that includes all carbon released back to the atmosphere). For agroforestry Equation (9) is minimized subject to different constraint:

$$P_t\delta_t - E_t - M_t + F_t \geq A_t + H_t - P_tC_tX, \tag{10b}$$

where the key difference between (10a) and (10b) is the inclusion of F_t*, the income gained from crops grown as a component of the agroforestry system. This study assumes a ten-year time horizon. To ensure payment compatibility at all times, it is assumed that for harvests prior to year ten the farmer must pay the market value of carbon released as a result of premature harvest. The carbon cost per ton is computed by dividing the net present value of the stream of payments by the total amount of carbon stored at the end of year ten*

Note that when computing the cost of carbon sequestration it is necessary to incorporate two opportunity costs associated with farm-level carbon storage: agricultural opportunity costs and the harvest value of an existing tree stand. To be consistent with the landscape under empirical study, three farm types are considered: both farm types discussed above (high-input vegetable farms and low-input maize farms), and unused land (on which no crops are cultivated, and hence the agricultural opportunity cost is zero). Based on slope classifications and site indices reported by Bin (1994), each farm type is assigned to three different zones of differing land qualities (low, medium, and high). This results in a matrix of nine representative farms − three each arrayed by land quality.

Using the series of payments derived by the cost minimization problem defined above, the cost of carbon per ton can be computed as:

$$\lambda = \frac{\sum_{t=0}^{T} \beta^t P_t}{C}, \tag{11}$$

where λ is the per ton present value of the total amount of carbon sequestered in year *T*.

To summarize, agricultural opportunity costs are computed as follows. For each representative farm a ten-year simulation is conducted using an optimization-simulation model of farm household behavior calibrated to the Manupali watershed (Shively and Zelek 2002). These simulations provide an income trajectory for each representative farm. Working backwards, starting in year ten, the net present value of the remaining agricultural income trajectory is computed for each year, using a 12% discount rate (based on a Philippines forestry sector report (ADB 1991)). This provides an estimate of the opportunity cost of converting land from agriculture to trees in any given year. For example, if one assumes a farmer were to keep his land in annual crops from years one to ten, the agricultural opportunity cost would be the net present value of production over the entire ten years. In contrast, if a farmer converted from agriculture to forest in year five, the opportunity cost of doing so would be the net present value of agriculture over the final six years.

For the agroforestry system, opportunity costs are computed in an analogous manner, assuming *P. falcataria* is intercropped with maize and vegetables. Following Nissen et al. (2001) annual crop yields are adjusted under intercropping due to both decreased soil erosion over the planning horizon and increased competition for light, nutrients, and water as the trees mature.

The harvest value of the plantation constitutes a second opportunity cost in this study. Harvest values are computed by multiplying the merchantable tree volume (determined in the carbon sequestration model) by a volume-dependent timber price. Wood volume is based on diameter at breast height for the age of the stand. The timber price is assumed to be constant at 350 pesos/m^3 based on 1998 data for the study area (Nissen and Midmore 1999). For both systems, tree spacing is assumed to be 5 m between rows and 2 m between individual trees.

Results and discussion

Table 3 reports total, marginal, and average costs of carbon sequestration (computed in present value terms). Marginal cost indicates the incremental cost of adding an additional unit of carbon for a particular representative class of farm. This ranges between \$3.30 and \$3.90 per ton of carbon sequestered on fallow land for both forestry and agroforestry systems. For fallow land, these costs are identical due to the absence of agricultural opportunity costs. When crops are grown, costs of storage via forests and agroforest diverge due to lower opportunity costs for agroforestry systems, hence lower carbon prices for conversion to agroforestry. On low-input farms the carbon cost ranges from \$25.00 to \$26.10 per ton for conver-

Table 3. Estimated total, marginal, and average costs of carbon sequestration in the Manupali watershed in the Philippines

		Forest			Agroforest		
Site Index	Cumulative Carbon (tons)	Total Cost (\$)	Marginal Cost (\$/ton)	Average Cost (\$/ton)	Total Cost (\$)	Marginal Cost (\$/ton)	Average Cost (\$/ton)
14	21787	84099	3.9	3.9	84099	3.9	3.9
18	110212	396238	3.5	3.6	396238	3.5	3.6
22	361070	1231595	3.3	3.4	1231595	3.3	3.4
26	1169037	21422683	25.0	18.3	20782541	24.2	17.8
30	2007086	42751044	25.5	21.3	41519346	24.7	20.7
34	2646815	59422380	26.1	22.5	57708806	25.3	21.8
38	3133430	891691131	61.1	28.5	80424354	46.7	25.7
42	3845477	133301841	62.0	34.7	114377601	47.7	29.7
46	4718652	187857778	62.5	39.8	156260469	48.0	33.1

Source: computed by the authors using equations reported in the text and site indexes reported by Bin (1994).

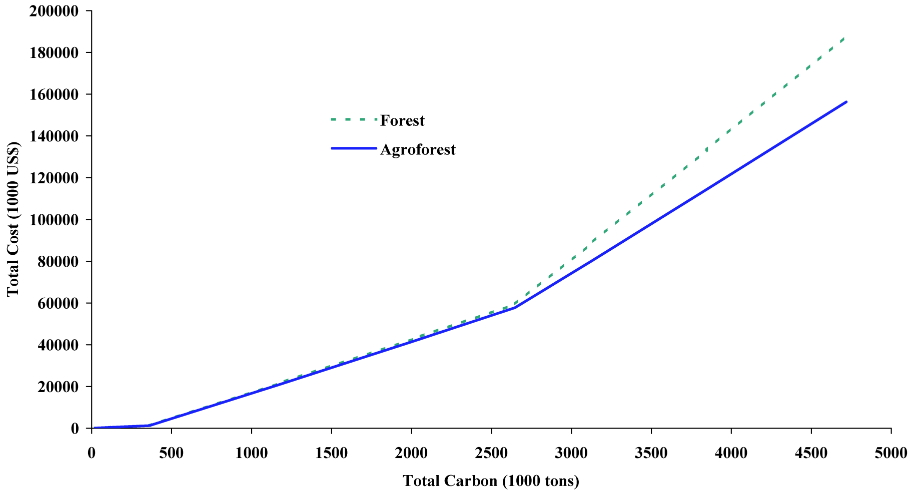

Figure 1. Estimated total cost curves for aggregate permanently fixed carbon in the Manupali watershed in the Philippines.

sion to forest and $24.20 to $25.30 per ton for conversion to agroforest. On high-input farms the carbon cost ranges from $61.10 to $62.50 per ton for conversion to forest and $46.70 to $48.00 per ton for conversion to agroforest. Average per-ton costs of carbon storage, i.e., the total cost of storing carbon divided by the total amount of carbon stored, are up to 17 percent lower in the agroforestry system than in the pure tree stand. Marginal costs are up to 23 percent lower.

These per-farm sequestration costs, and relevant land classification data from the watershed, were used to estimate total costs of reaching an aggregate carbon target in the watershed. The amount of potential carbon storage per hectare was first computed, which provided an estimate of total potential carbon storage in the watershed. These values were then used in conjunction with the marginal cost for each site index classification to estimate cumulative total costs of sequestration, assuming land would be converted in rising order of productivity. Average costs were computed by dividing the total cost for each site index by the corresponding cumulative carbon stored at that site. As data in Table 3 illustrate, average costs are consistently lower than marginal costs for both forestry and agroforestry, ranging from $3.30 on fallow land in both cases to $39.80 for forestry conversion and $33.10 for agroforestry conversion. That average cost lies everywhere below marginal cost reflects increasing marginal costs. In other words, as the carbon target rises, it becomes necessary to use land of increasingly higher quality (and hence value) to meet the carbon target.

To further illustrate these patterns, total costs of carbon sequestration in the Manupali watershed are displayed in Figure 1. These data are based on aggregate land areas available for conversion, cataloged by site index and land use in 1996. Figure 1 shows the total cost of carbon sequestration corresponding to a specific carbon target. The total cost curve for agroforest is identical to that of forest up to the point where the carbon target exceeds 361,000 tons (the amount of storage potential on fallow land). The first kink in the graph occurs where the curves diverge as land planted to maize enters the base for conversion. In this case, the cost curve for agroforest lies below that for forest at all points because the addition of annual crops in the agroforestry system compensates for some of the opportunity cost of converting from annual crop agriculture, especially in the early years of the planning horizon. This trend continues up to a carbon target of 2.6 million tons, the total carbon storage potential for fallow and maize land in the watershed. Beyond this second kink in the graph, sequestering carbon via forest and agroforest diverge further, due to the need to convert from vegetable cropland, which carries a higher opportunity cost of conversion. The total estimated carbon storage potential of the 60,000-hectare watershed is 4.7 million tons. This storage level is associated with a total present value cost of $188 million for pure forest and $156 million for agroforest.

These estimates of per-ton costs of carbon storage associated with conversion of fallow land are comparable to low estimates previously appearing in the literature. For example, Adams et al. (1999) estimate a cost of $5 to $21 per ton associated with sequestering carbon in U.S. forests and agricultural sectors. Although a number of studies suggest carbon sequestration costs in forestry below $5 per ton (see, for example, www.wri.org/wri/climate/sequester.html accessed 01 Nov 2001), many studies fail to account for the opportunity cost of converted land. This study's shows that when the opportunity cost of productive agricultural land is taken into consideration, carbon prices derived from afforestation rise significantly and fall within the lower end of the US Department of Energy's estimated range for industrial source reductions and fuel switching (www.fe.doe.gov/coal_power/sequestration/index.shtml accessed 01 Nov 2001).

The implication of planting an entire watershed with trees is, of course, difficult to assess. In theory and in practice large scale conversion of agricultural lands to tree plantations could result in lower prices for trees and higher prices for food. Such general equilibrium effects are not accounted for in this study. Instead we assume that land-use changes in a single isolated watershed are unlikely to result in measurable changes in the larger economy. While this assumption is perhaps warranted in the case of agricultural prices, an increase in the local supply of some tree and timber products could depress prices of these products. Price reductions, in turn, would make tree planting for carbon sequestration relatively more costly. Some anecdotal evidence from Mindanao suggests that the local market for timber products is fairly robust. Price declines have not accompanied recent increases in local supply.

Conclusions

This study presented a method for measuring the costs of sequestering carbon via conversion to forestry or agroforestry systems. The method relies on constructing a measure of the opportunity cost of current land uses and computing time-consistent compensating payments for changes in land uses. The latter can be derived as the result of an inter-temporal cost-minimization problem.

Data from the Philippines were used to provide estimates of total cost curves for land conversion, as well as the corresponding marginal and average costs for carbon sequestration. The analysis shows that as the total amount of carbon sequestered rises, the opportunity cost of land conversion increases due to both changes in land quality and changes in land use. Low quality fallow land has the lowest opportunity cost and high quality land planted with high value crops has the highest opportunity cost. An agroforestry system is found to be a lower-cost alternative to pure forest conversion, with average per-ton carbon costs that are approximately 8-16 percent lower than the costs for carbon storage via a pure tree stand. The estimated cost of sequestering carbon over a 10-year period in the Manupali watershed ranges from $3.30/ton on fallow land to $62.5/ton on land planted to high value crops if replaced by forest, and $3.30/ton to $48.00/ton if replaced by agroforest.

Among the possible methods for sequestering carbon in biomass, the Kyoto Protocol's Clean Development Mechanism (CDM) permits site-specific activities that increase carbon storage and hence reduce net carbon emissions. Such site-specific activities might include restoration of deforested or degrading forest lands or expansion of the area or carbon density of agricultural landscapes, through agroforestry. The argument for re-forestation via agroforestry rather than by forestry is strengthened by the data presented in this study. Results suggest that carbon storage via conversion of the lowest-value degraded agricultural lands may be cost-effective, although the cost of sequestering carbon rises rapidly as the carbon target for the landscape increases and highly productive agricultural land must be used to meet the carbon target. Agricultural land in low-income tropical settings varies widely in both opportunity cost and carbon storage potential. As a result, efforts to design mechanisms to support carbon sequestration by smallholder farmers, whether through forestry or agroforestry, will have to account for landscape heterogeneity.

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